Scaling combs into the XUV

Scientists have transferred coherence from a near-infrared frequency comb laser to the extreme-ultraviolet region with no detectable noise. Jun Ye and co-workers explain that this might impact fields from fundamental physics to nuclear clocks.

What are the motivations for working on extreme-ultraviolet technology today?

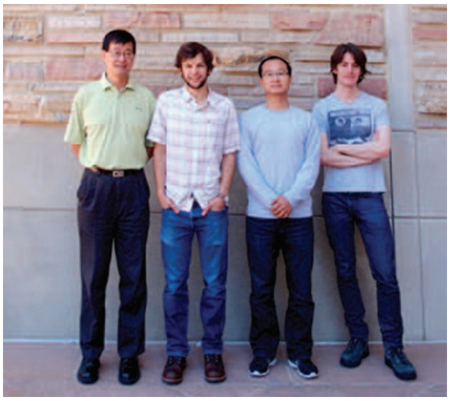
The extreme-ultraviolet (XUV) spectral range is a largely unexplored frontier for high-resolution laser spectroscopy. Until very recently, no one thought it possible to have access to continuous-wave-like radiation in this spectral region. Now, with the convergence of ultrafast laser science, strong-field physics and precision measurements, it has become possible to venture into this region. This opens the door for new scientific opportunities in precision measurement, high-resolution spectroscopy and strong-field science. There are many simple atomic systems, such as H-like and He-like ions, which possess long-lived excitations of fundamental interest that exist only in the XUV region. We now have the ability to go after them. Furthermore, the possibility of using phase-stable XUV radiation to probe long-lived nuclear transitions and highly charged ion species, possibly for next-generation nuclear clocks, is truly exciting.

What did you achieve in your present work?

We have demonstrated that the process of high-order harmonic generation (HHG) is extremely phase coherent, which was not obvious given the highly nonlinear nature of HHG. We have shown that we can faithfully transfer the coherence of our frequency comb laser in the near-infrared region to the XUV region with no detectable noise arising from fundamental processes. We have identified the scaling properties of technical noise and shown that they can be experimentally controlled to a negligible level. In summary, we can show that billions of XUV pulses, each separated by nanoseconds, remain phase coherent throughout. In other words, each XUV comb can have a spectral resolution of below 1 Hz. That is astonishing.

What are the implications?

XUV radiation with coherence properties comparable to those of radiation produced by the best available visible lasers is groundbreaking. The spatial coherence of XUV sources was demonstrated early on, but the spectral resolution of XUV remained basically uninvestigated until recently.



NIST/UNI. OF COLORADO BOULDER

Jun Ye, Craig Benko, Linqiang Hua and François Labaye (left to right) together with (not pictured) Thomas Allison, Arman Cingöz and Dylan Yost from NIST and the University of Colorado at Boulder in the USA have demonstrated XUV radiation with a coherence time beyond 1 s.

Earlier work started to show that we could achieve spectral coherence akin to a comb structure, leading to demonstrations of spectral resolution at the megahertz level in 2012. However, it remained uncertain whether we could truly realize a similar kind of spectral coherence in the XUV region as that demonstrated in the visible domain. We have now reached this goal. As this spectral region is largely unexplored for precision spectroscopy and measurement, many surprises and exciting new results await us. Another important consequence is that phase-stable XUV light can be used to probe attosecond dynamics that are imprinted on the phase information of the light originating from HHG. In some sense, we are probing the physics of the ultrafast (strong-field physics) with the tools of the ultraslow (high-resolution frequency metrology).

What was the most experimentally challenging aspect?

The experiment follows the basic scheme we demonstrated about nine years ago (Jones, R. J., Moll, K. D., Thorpe, M. J. & Ye, J. *Phys. Rev. Lett.* **94,** 193201; 2005) using passive femtosecond enhancement cavities to build up a sufficiently high pulse energy for HHG without decimating the repetition frequency. We perform HHG inside the enhancement cavity and extract it with a variety of techniques. Recent advances in Yb:fibre laser technology have made our work easier, and we only have to rely on enhancement cavities with a moderate finesse. The high-average-power frequency comb was essential for creating two XUV frequency combs in two separate femtosecond enhancement cavities. Building an interferometer in the XUV region was no trivial task. In the visible region, beam splitters, mirrors and lenses abound, whereas you have to be a bit more creative in the XUV region! Despite the limited amount of optics and diagnostics, we were able to construct a phase-stable interferometer that worked over an order of magnitude wavelength range (from 1,070 nm to 56 nm). We needed to use B_4C-coated mirrors and a newly designed beam combiner made of a mirror with a small aperture. We also had to interferometrically combine two independent XUV beams that originated inside two femtosecond enhancement cavities under vacuum.

Can the performance be pushed further?

We haven't found any fundamental limit on the temporal coherence of XUV radiation produced by HHG. Certainly, quantum physics will impose an ultimate limit. However, we have shown that HHG is compatible with the best available lasers. We have plans to extend our measurements to even shorter wavelengths, where there are many exciting spectroscopic applications in H-like and He-like ionic systems. We are very excited about the possibilities that arise when you have clear access to the phase of XUV radiation originating from HHG. A lot of experimental effort has gone into trying to extract phase information. Our system provides unique access to phase by allowing millions of optical fringes to be sampled, enabling phase information to be extracted with a high fidelity. We feel that the system is well suited for testing the most advanced theories of HHG in atoms and molecules.

INTERVIEW BY DAVID PILE

Ye and co-workers have an article on extreme ultraviolet radiation with coherence time beyond 1 s on page 530 of this issue.

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